SOUNDRIVE ENGINE COMPANY

AD 13144

FINAL REPORT

on the

HIGH AMPLITUDE SOUND ABATEMENT RESEARCH PROGRAM

for the Office of Naval Research

Contract N8 onr 70502
Project NR 014-907

Contractors Serial Report No. 49

February 1953

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CONTENTS

I. Introduction

1.1 Brief History of Program

This high amplitude sound research program was initiated in 1948 by the U.S. Naval Air Missile Test Center at Point Mugu, California for the following reasons: (1) To ascertain basic data and the methods available for dissipating exceptionally high noise levels at low frequencies without incurring large back pressure to engine exhaust, etc., and (2) to provide a means of testing prototypes of the designed systems.

The initial phases of the program were completed through the joint efforts of the Office of Naval Research, the Naval Air Missile Test Center, the Parsons-Aerojet Company, and acoustical consultants R. W. Leonard and I. Rudnick of the Department of Physics of the University of California.

A powerful siren as a sound source, a test pipe and instrumentation were designed, constructed and a number of tests run on them prior to the deferment of the project in 1949.

The principle results of these tests were to establish:

(1) The feasibility and reliability of the siren as a sound source.

(2) The feasibility of utilizing two Packard Merlin aircraft engine superchargers as an air supply for the siren provided there was additional cooling of the air.

(3) The existence of high attenuation rates for shock type acoustic waves.

In 1950, work was resumed on this program. At this time

Soundrive Engine Company entered the picture for the first time. Professors Leonard and Rudnick were again retained to guide the technical aspects of the research. The sound source and test apparatus were moved from their original location at Point Mugu to this contractor's test site in DeWitt Canyon near Newhall, California, not far from Los Angeles. Work then commenced to carry out the remainder of the task order of contract N8 onr 70502.

1.2 Task Order

(1) Conduct basic research on the suppression of high amplitude low frequency sound, to include investigation of the following acoustical phenomena:

(a) Attenuation of sound in a rigid walled tube, including investigations of tubes of different diameters if data indicates the desirability thereof;

(b) Attenuation of sound due to water droplets;

(c) Properties of acoustical filter elements;

(d) Design and test of multi element acoustic networks; and

(e) Design and test of acoustically-absorbing material for use in intense sound.

(2) Conduct tests on sound abatement devices originating under other Government research programs; and

(3) Locate and establish sound abatement facilities in the Los Angeles area. This work shall include moving available equipment from Point Mugu to the Los Angeles facility, re-installment of such equipment

and conducting tests with such equipment.

II. Summary of Progress and Results

In order to make this summary succinct it will be itemized.

1. The development of the siren, air supply and associated equipment has resulted in a sound source capable of delivering continuous acoustic power into a 10" diameter tube at acoustic levels of up to 100 kilowatts, the temperature of the tube not exceeding 170°F. The frequency range is 20-200 c.p.s.

2. Considerable effort has resulted in the development of a condenser microphone system which has proven to be accurate and reliable for essentially continuous use in acoustic fields where the pressure swing approaches one atmosphere. The reliability is such that it seems suitable to use such a system in standardizing work for high acoustic amplitudes.

3. A large amount of data on the attenuation of high amplitude plane waves has been collected. Theories of the attenuation of such high amplitude waves have been developed and examined. It has been established that the measured attenuation rates are generally lower than those theoretically expected. There is at present no adequate explanation of this surprising result.

4. Preliminary measurements have been made on (a) the effect of water spray on the attenuation rates and (b) the impedance at resonance of a Helmholtz resonator used as a side branch.

III. Details of Progress and Results

3.1 Principle Components of Apparatus

3.11 Air Supply, Siren and Associated Equipment

These are described in some detail in Technical Report No. 2. A brief description of the principle components follows:

(1) An air supply consisting of two Packard-Merlin aircraft engines modified to use the supercharger as an air compressor which is capable of delivering about 10 pounds of air per second at a gauge pressure of about 12 or 13 p.s.i. The output is limited due to flow resistance imposed by the use of air coolers.

(2) A 5000 gallon water storage tank to provide cooling of the engines.

(3) An air supply feed system.

(4) A surge tank which acts to block upstream travel of the sound waves.

(5) A 20 to 200 c.p.s. siren having four ports of approximately 10 in^2 area each. This air supply-siren combination is capable of producing approximately 100 kilowatts of acoustic power at an efficiency of about 40 percent.

The air supply and siren have consistently given trouble-free operation.

3.12 Measurement Tube and Associated Components

A sixty foot long 10" ID steel tube is coupled to the siren through a diffuser section designed so that there is negligible acoustic reflection

when the area is increased from the total area of 40 square inches of port openings to the cross sectional area of 79 square inches of the tube. The tube is fitted with a track and motor driven pulley system for continuously moving the measuring microphone. An auxiliary fitting which has not thus far been used is a by-pass section for diverting the d.c. air flow. Appropriate ports are provided for coupling resonators, etc. to the tube.

3.13 Acoustic Termination for Measurement Tube

At the downstream end of the measurement tube a tapered fiberglas termination 10 feet in length is provided. The purpose of the termination is to reduce acoustic reflection for the progressive wave in the tube. The approximate reflection coefficient at maximum power output for the siren is shown in Fig. 1.

The absorbing material, unbonded TWF fiberglas compressed to a density of about 7 lb/ft^3, is held in the inner and outer walls of the cone by, successively, interspersed layers of cheesecloth, 8 x 8 mesh hardware cloth, and the walls of the cone, sheet steel perforated with 1/4" holes, 5/8" between centers. The schematic outline of the acoustic termination is shown in Figure 2. One difficulty encountered is that at these high amplitudes the fiberglas is pulverized and blown away after some use. When this happens the termination must be repacked.

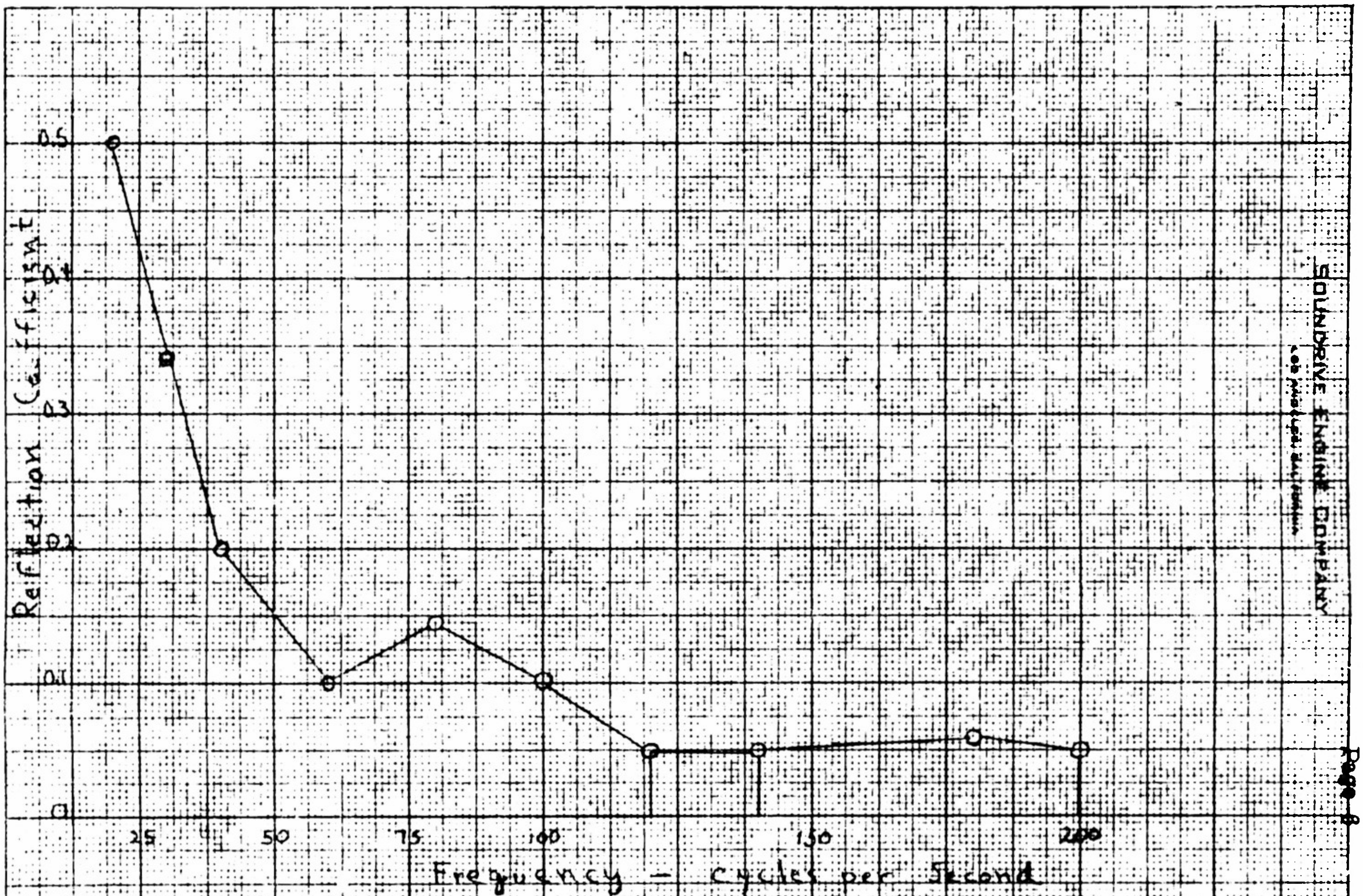

Figure 1 - Approximate values of reflection coefficient of siren tube termination at maximum siren power output.

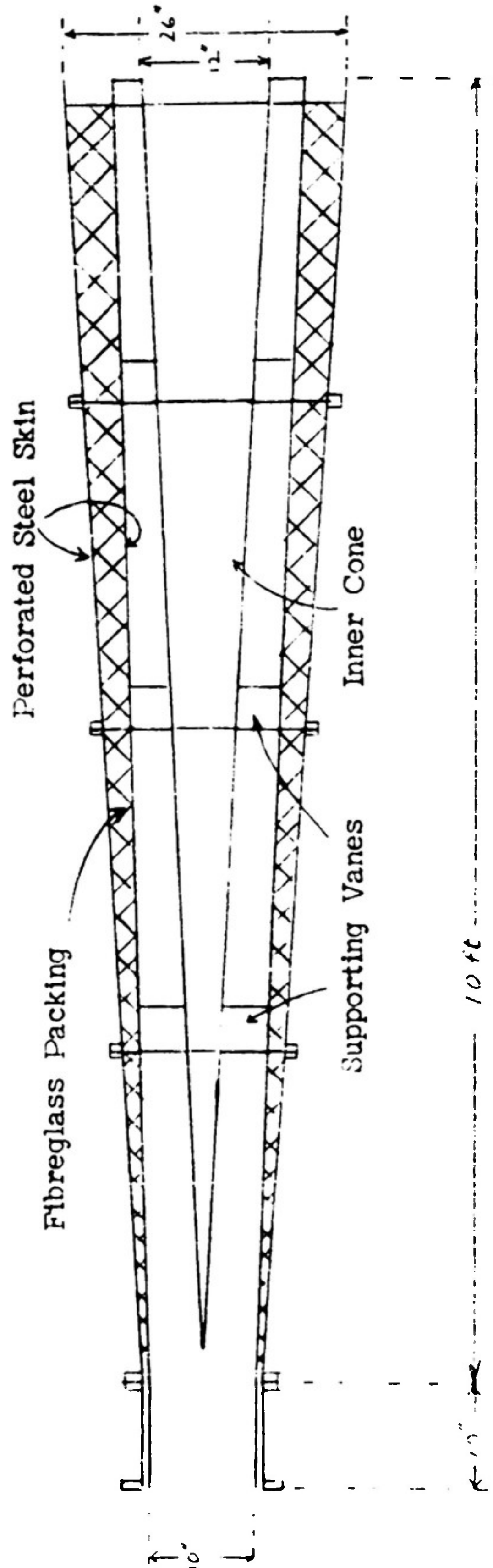

Figure 2 SIREN PIPE TERMINATION

3.14 Microphones and Associated Electronic Components

Considerable effort was expended in the development of a satisfactory microphone. Early attempts at using a diaphragm actuated magnetostriction microphone were abandoned following the discovery that its sensitivity was quite dependent upon temperature. Effects of the extreme temperatures on microphone cables were detrimental, also.

As a result, it was decided to install the coolers on the air supply system and to return to a condenser microphone (in the earlier experiments at Point Mugu a condenser microphone was used) for installation in the carriage in the sound measuring tube.

The diaphragm and case of this microphone were machined from an integral piece of cold rolled steel. The diaphragm was 1-1/4 inches in diameter and about 0.026 inches thick. The spacing between the diaphragm and rear electrode was set at about 0.003 inches. The case was screwed onto a machined brass support which contained a cathode follower and cable connection. Washers and a spring held the glass insulator supporting the rear electrode in place. A schematic drawing of the microphone assembly is shown in Figure 3.

This microphone served quite well for some time after which there occurred a sudden drop in sensitivity of about 2 db. No suitable explanation for this has been found.

Another similar microphone was now constructed of machinery steel and tested. During construction, the material was stress relieved by heat treatment just prior to final machining. Careful testing showed

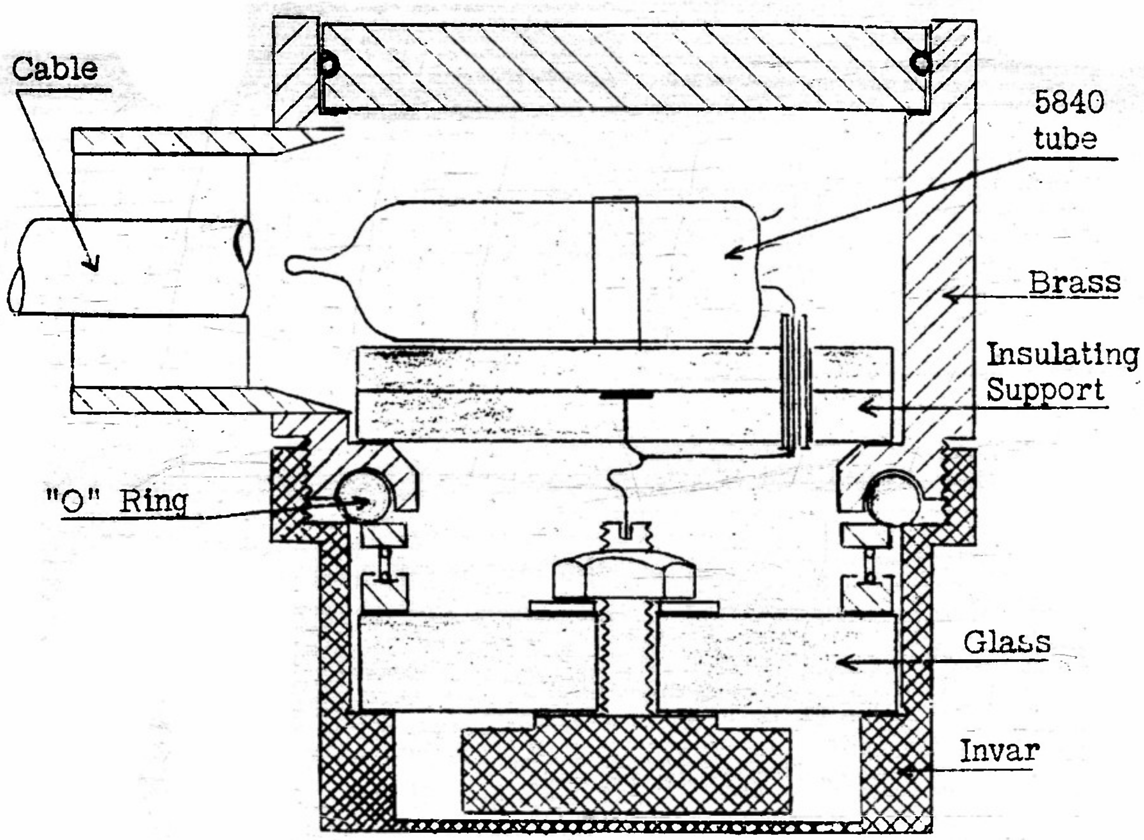

Figure 3

Schematic outline of car microphone.
Scale: X2
Details of preamplifier and cable wiring
not shown.

an undesirable change in sensitivity with temperature changes occurring in the siren sound field.

A third car microphone was then built. The material used here was free machining Invar to reduce the temperature effects. Use of this microphone has shown that it is a very stable and reliable instrument.

A condenser microphone constructed at the beginning of this program which was designed for auxiliary, stationary use has mechanical features which are only slightly different from those of the car microphone. Its diaphragm and diaphragm support are integral as in the car microphone, and the dimensions and sensitivity are nearly the same as those of the car microphone. The auxiliary microphone has served principally as a reference of sensitivity for the car microphone and has not been continuously subjected to the intense acoustic fields as has the other. Its sensitivity has remained unchanged since its first calibration. Calibration results are given in Section 3.21.

Two methods were used in the field for comparing them. One, comparison of outputs when the two microphones were placed side by side in the sound field of the siren, was not entirely satisfactory. The second method involved the use of an electromagnetic induction to cause diaphragm displacement and gave more nearly reproducible results. Data on comparisons are presented in Section 3.21.

It is easily noticed and is to be expected that the microphones show a resonant peaking of sensitivity in the neighborhood of 5500 c.p.s. A

large spacing between the diaphragm and rear electrode is required in this microphone in order to reduce its acoustic sensitivity and sensitivity to the thermal expansion effects, hence, very little damping of the first resonant mode of the diaphragm can be obtained.

To reduce the effect of oscillations of the diaphragm caused by the shock waves, a band stop filter, tuned to the resonant frequency of the microphone diaphragm is inserted into the electrical system. The Q of the filter is adjusted so that the whole system gives a satisfactory oscilloscope reproduction of a sawtooth wave of fairly low repetition rate. The resulting overall sensitivity at this resonant frequency is only slightly lower than at the low frequencies. Graphs of response to electrostatic actuation are presented in section 3.21.

The power for operation of the condenser microphones is provided by a Altec P-518A Power Unit modified by removal of the output transformer and filter circuits.

The a.c. signal from the cathode follower at the microphone is amplified and rectified by a Hewlett-Packard Model 400-C vacuum tube voltmeter. The d.c. voltage across the current meter terminals, which represents an average of the a.c. signal input, is connected to the input of a Brown recording potentiometer. The motion of the recording paper in the recorder is synchronized with the motion of the microphone in the sound tube, resulting in a continuous graph of average pressure swing as a function of distance from the siren. A means for the convenient checking and adjustment of the voltmeter-recorder calibration is provided.

3.2 Measurements

3.21 Microphone Calibrations

The two condenser microphones (car and auxiliary microphone) received on several occasions careful free field calibrations, using as a standard for comparison, a Western Electric 640-AA condenser microphone which had been previously calibrated by a reciprocity method. Only a normal incidence position relative to the sound field was used. The arrangement of the sound source and microphones was varied for different frequency ranges to reduce effects of angular variations in the radiation pattern from the source, etc. It is believed that the accuracy of calibration is at least within plus or minus one half decibel.

A typical calibration curve for the car microphone is shown in Figure 4. (The present car microphone (Invar) has a similar curve -- but is about 1 db less sensitive).

It seems very likely that the resonant peak at the frequency of about 6000 c.p.s. is due to both diaphragm resonance and to diffraction effects at the microphone.

Figure 5 shows a calibration curve for the auxiliary condenser microphone. A six month time interval elapsed between the taking of the two sets of data shown, during which time the microphone was used in the intense sound field. This offers a basis for belief in the stability of this microphone.

As stated earlier, the car microphone amplifier circuit included a band stop filter, the purpose of which was to reduce on the

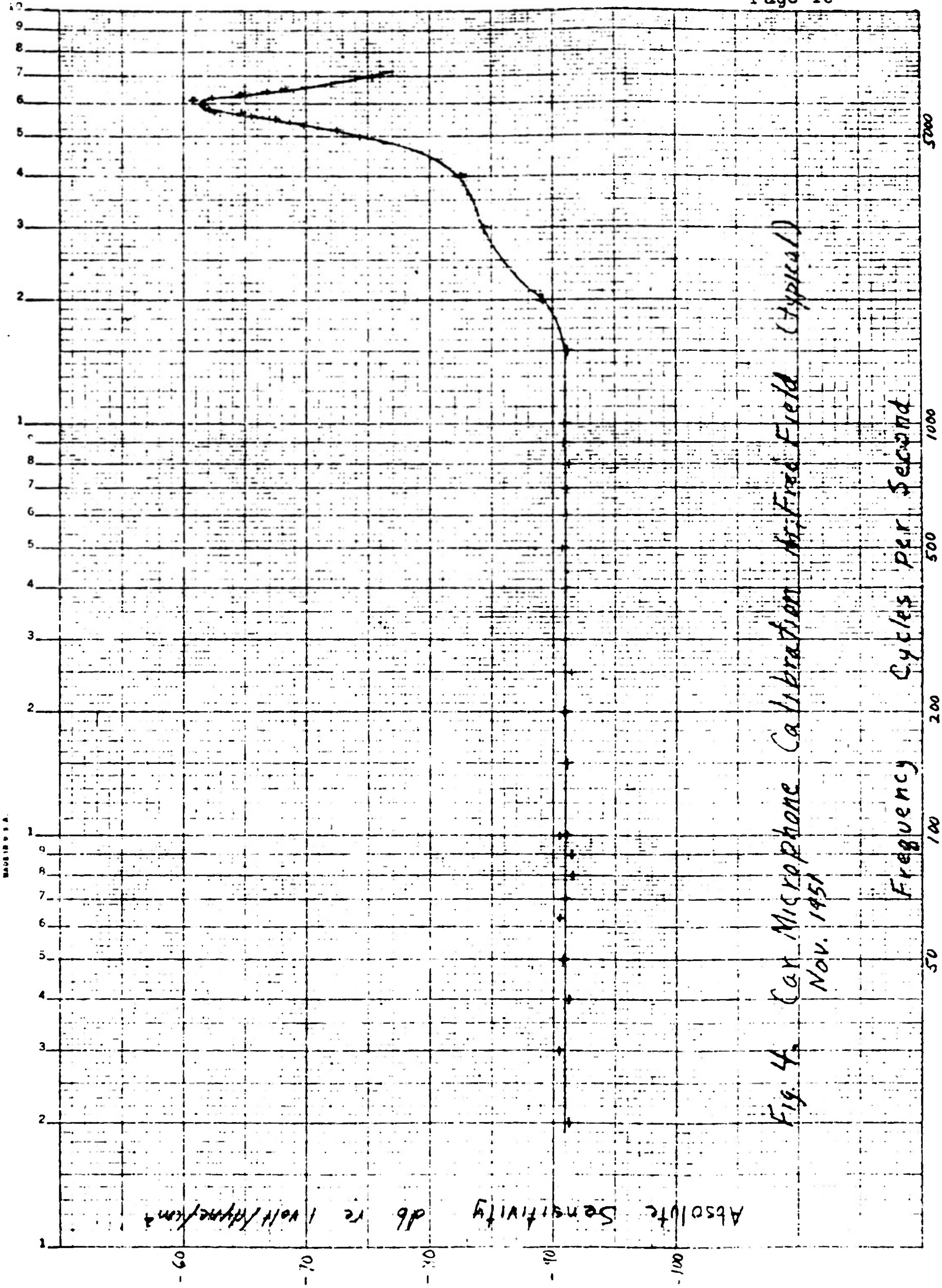

Fig. 4. Car Microphone Calibration Air: Free Field (typical)
Nov. 1951

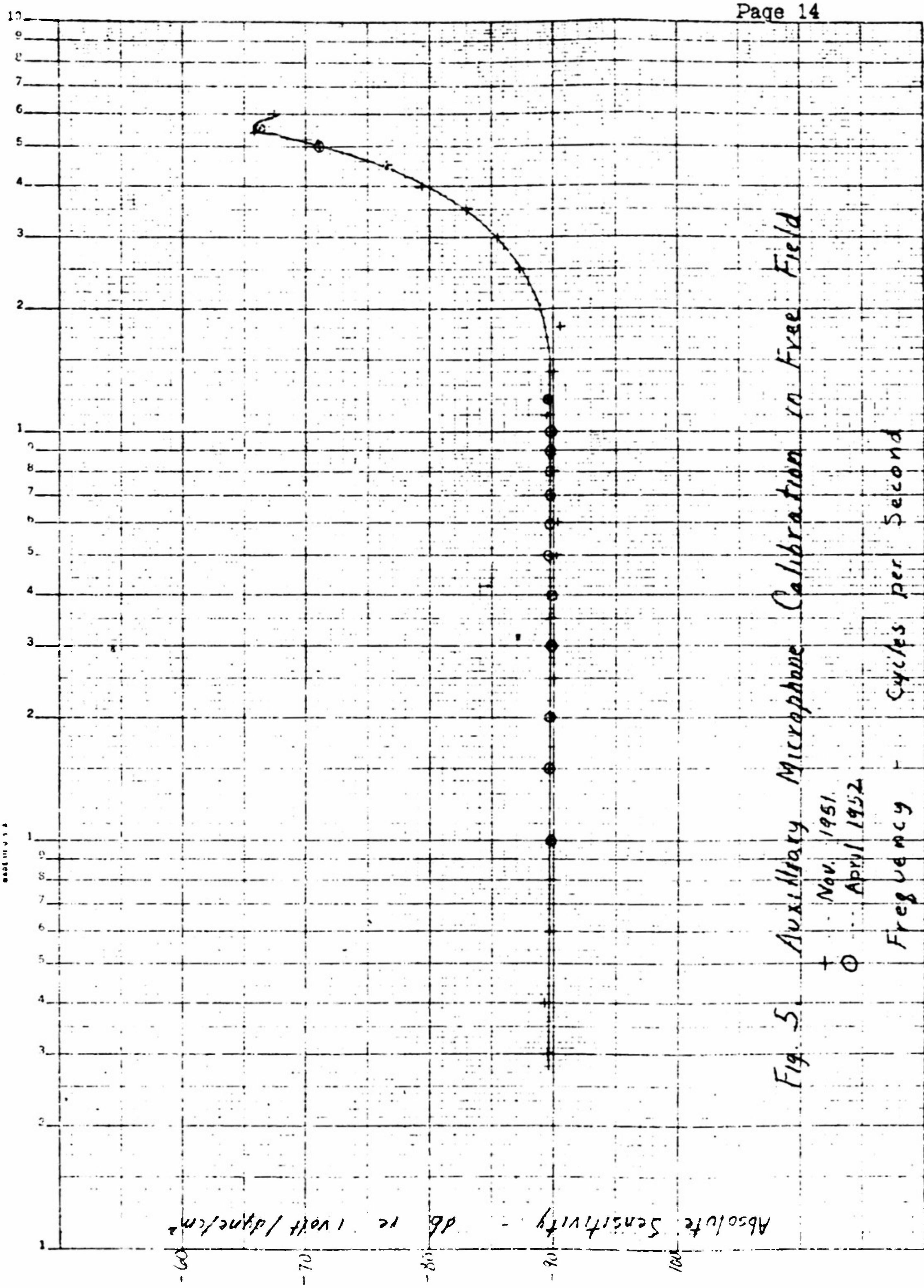

Fig. 5 Auxiliary Microphone Calibration in Free Field

oscilloscope trace the undesirable oscillations arising from shock excitation of the diaphragm. The adjustment of the filter is made in the laboratory using electrostatic excitation with a sawtooth or square wave form. The Q and resonant frequency are varied to reduce the shock excited oscillations to a low value without causing too much lowering of the rise time.

In a check of the overall response of the microphone-filter arrangement, an electrostatic actuator was used. This method of excitation gives a frequency characteristic which is more nearly like the pressure sensitivity of the microphone than does a free field-normal incidence method. Figure 6 is a graph of the results of the actuator measurements showing the actuator response for the microphone alone and for the microphone-filter combination. It is felt that the performance of the combination can be improved.

3.22 Experimental Results on the Attenuation of a Repeated Shock Wave

This is reported in detail in Technical Report No. 3. A brief discussion follows:

Measurements were made on the variation of amplitude of the sound wave with distance of propagation down the tube. This was done at several acoustic frequencies in the range 30-200 c.p.s. and at several power levels of operation of the siren. It was found that when the siren chamber pressure was at a maximum (22.4 inches Hg) the sound waves in the tube had shock fronts, were sawtooth in form and could be characterized by the phrase "repeated shock wave." Moreover at the lowest

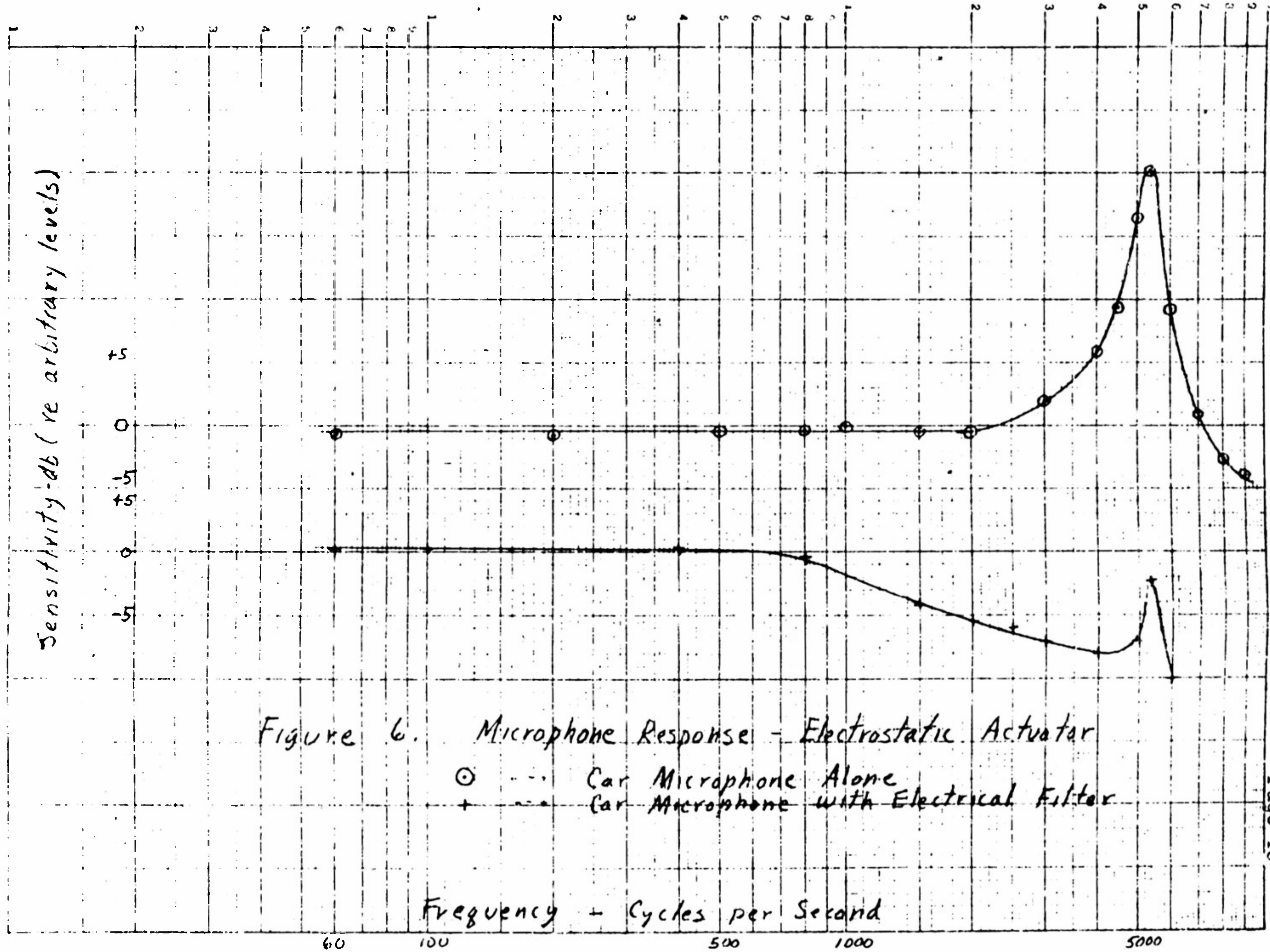

Figure 6. Microphone Response - Electrostatic Actuator

power level of operation (chamber pressure equal to 1.5 inches Hg) the sound waves were repeated shock waves for all frequencies above 60 c.p.s. At lower frequencies the shocks were not fully developed at the siren end of the tube.

The measurements involved photographing the oscilloscope trace of the sound wave, an example of which is presented as an insert on Figure 7, and automatically recording the rectified average voltage produced by the condenser microphone mentioned earlier. Data pertaining to waves in which the shock was not fully developed was not used in the analysis of attenuation rates.

The rectified voltage was converted into equivalent pressure change across the discontinuity.

Of principle interest in these propagation studies was the effect on the attenuation due to the shock character of the wave. Accordingly a correction (which generally was small) was made for the viscous and heat conduction losses of energy at the walls of the tube. Also correction was made for the convective flow of air down the tube.

A theoretical result (see section 3.31) for low amplitude repeated sawtooth shock waves is that the amplitude should follow the law

$$\frac{1}{\delta} - \frac{1}{\delta_0} = \frac{\gamma + 1}{2\gamma} \cdot \frac{x - x_0}{\lambda} \qquad (1)$$

where $\delta = \dfrac{p_2 - p_1}{p_1}$

p_1 = pressure on the high pressure side of the shock

p_2 = pressure on the low pressure side of the shock

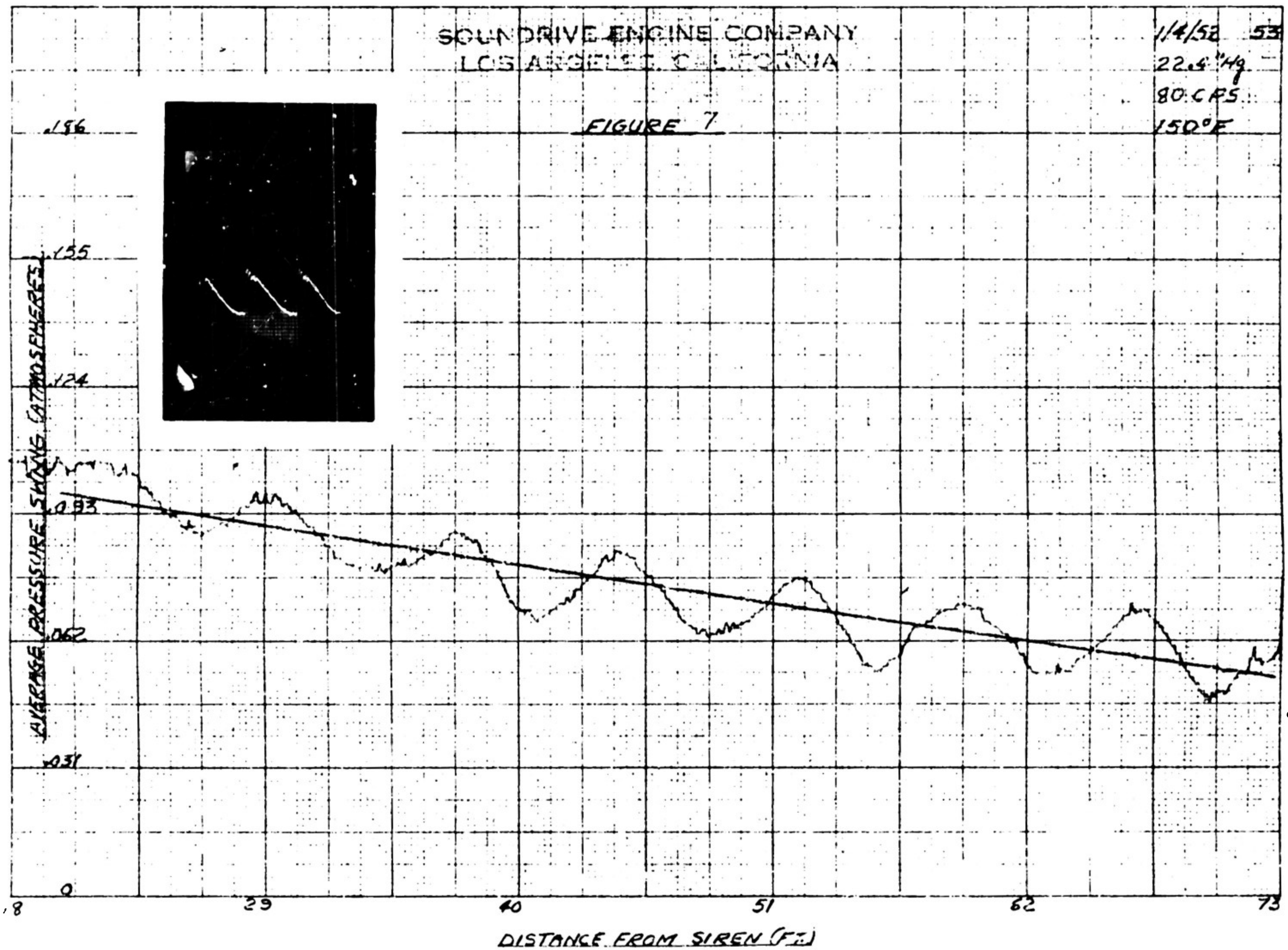
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FIGURE 7
1/4/52 53
22.4" Hg
80 CPS
150°F
AVERAGE PRESSURE SWING (ATMOSPHERES)
.186
.155
.124
.093
.062
.031
0
18
29
40
51
62
73
DISTANCE FROM SIREN (FT.)

δ_o = value of δ at $x = 0$

λ = wavelength

γ = ratio of specific heat at constant pressure to the specific heat at constant volume.

Thus when $\frac{1}{\delta}$ is plotted against X a straight line of slope $\frac{\gamma+1}{2\gamma\lambda}$ should result. The observed data when plotted in this way seems to satisfy the straight line relationship reasonably well; however, the measured slopes lie between 50% and 100% of that given by the theory. Most of the values are close to 70%. A set of data obtained at a frequency of 140 c.p.s. is shown in Figure 8.

The theoretical result given by formula (1) properly holds for values of δ which are generally lower than those measured. An extrapolation of the observed data to lower values of δ indicates that there is little possibility that the slope will become as great as $\frac{\gamma+1}{2\gamma\lambda}$.

3.23 Attenuation Measurements With Large Amplitude Sound Waves in a Water Spray

The arrangement of apparatus for this experiment is very similar to that used for the attenuation measurements discussed in Technical Report No. 2. The sound waves from the siren together with the d.c. air flow travel through the 10 inch diameter measuring tube where a traveling microphone permits measurement of the sound level throughout a length of 60 feet of the tube. The only modification consists of the addition of a water spray nozzle arrangement at about the middle of the 60 foot measuring tube. The average sound pressure level is recorded as a function of distance along the tube for a variety of frequencies, sound pressure levels

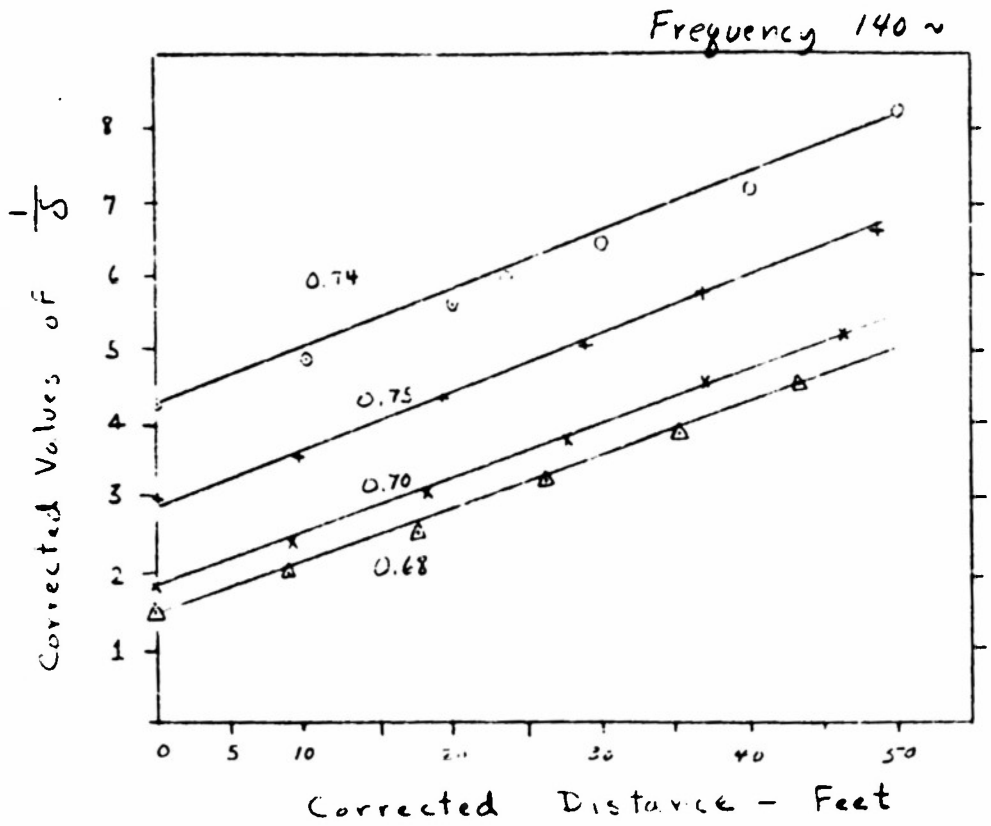

Figure 8

Plot of observed results: Corrected values of 1/δ versus corrected distance. The number associated with each line is the ratio of the observed slope of the line to the theoretically expected slope.

and water flow rates.

Data supplied by the manufacturer of the nozzles permitted a determination of droplet size distribution and flow rate from the operating pressure at the nozzle. The accuracy of this determination is probably limited, however, due to difference from the spray environment specified in the manufacturer's measurements, i.e., here, the spray was injected into a relatively fast moving stream of warm air confined in a pipe. No efforts were made to study droplet size in the tube. Approximate air flow rates were determined from published data for the blowers furnishing air for the siren.

Pertinent Data

Frequency Range covered: 80 to 160 c.p.s.

Average Pressure Swing in Water Spray Region (Sawtooth wave form):

ranged from about 0.05 to 0.08 atm.

Water Flow Rate, Maximum: about 56 lb/minute

Air Flow Rate: 400 to 460 lb/minute

Ratio $\frac{\text{Water flow rate}}{\text{Air flow rate}}$: 1/10 to 1/7

Nozzles: Two Whirljet 3/8A 15-25 conical spray nozzles

Water Pressure: 30 psi

Particle Size: Average about 100 microns (70% of particles were within the size range of 25 to 150 microns)

The results may be summarized:

(1) The additional attenuation provided by the water spray is observable but is sufficiently small to make accurate measurement difficult

for the small water/air ratio used here. No profound attenuation effect due to the water spray is indicated.

(2) Also, no clear indication of frequency dependence was found.

No theoretical computation of attenuation was attempted for the reason that the harmonic structure of the sawtooth pressure wave form precludes a simple computation of attenuation using the presently available formulae for attenuation of sound in aerosols.

3.24 Impedance of Resonators at Large Amplitudes

Preliminary measurements were performed of the shunting impedance presented by a resonator placed in the wall of the 10" tube. Two resonators were employed singly. Both resonators had a tubular volume of 1.07 cu. ft. Resonator A had a cylindrical neck of length 2 in. and diameter 3 in. Resonator B had a cylindrical neck 4 in. in diameter and 4.25 in. long. The low amplitude Helmholtz resonator frequency was about 56 c.p.s. for both. A resonator (A or B) was placed about halfway down the tube as shown in Fig. 9.

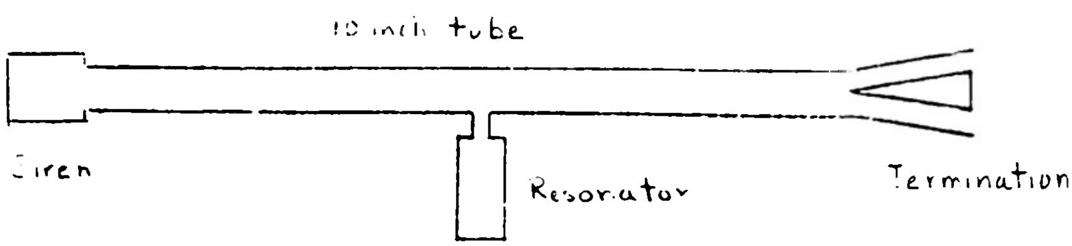

Figure 9

Measurements were made under conditions where the acoustic particle

velocity amplitude in the neck of the resonators ranged from $.7 \times 10^4$ to 1.2×10^4 cm/sec. In all cases the combination of the resonator and the portion of the 10" tube downstream of it appeared to be resistive when the sound frequency was equal to the low amplitude resonant frequency of the resonator. Further analysis of the standing wave structure at this frequency indicated that in the six cases (various particle velocity amplitudes) studied the impedance R, of the resonators was real and given by

$$R = \frac{1}{2} \rho_0 \frac{U_0}{S}$$

where ρ_0 is the equilibrium density of the air, U_0 is the particle velocity amplitude of the sound wave in the neck of the resonator and S is the cross sectional area of the neck. These findings are in agreement with those of Sivian (Journ Acoust. Soc. Am., 7 94, 1935).

It should be pointed out that an added complication in the measurements is occasioned by the fact that the wave traveling down the tube is sawtooth in character. However, all the above discussion refers to the fundamental of the complex wave, a filter being employed in the measurements.

Further experimentation awaits improvement of the termination to better approximate zero reflection.

3.3 List of Technical Reports Issued

Technical Report No. 1

"Theory of the Attenuation of Very High Amplitude Sound Waves" by I. Rudnick. Contractors Serial Report No. 42 (July 1952)

Technical Report No. 2

"Instrumentation and Apparatus for a High Amplitude Sound Research Program" by Robert W. Leonard and O.B. Wilson, Jr. Contractors Serial Report No. 45 (October 1952)

Technical Report No. 3

"Measurements of the Attenuation of a Repeated Shock Wave" by I. Rudnick. Contractors Serial Report No. 48 (Feb. 1953)

IV. Concluding Remarks

4.1 Experience with High Amplitude Acoustic Fields

One of the results of the investigations which is difficult to report, but which is nevertheless important, is the background of experience which has been gained. This experience may be of such a nature as to give the experimenter sufficient knowledge to make qualitative judgments, to make intelligent guesses, or to be able to plan further experiments. It is precisely because of the diffuse and non-quantitative nature of the experience that it is difficult to report. It is felt worthwhile to report, in any case, on certain specific items.

4.11 Velocity and Pressure Measurements in the Presence of High Amplitude Acoustic Fields

Consider a typical Pitot tube and U-tube manometer shown schematically in Figure 10.

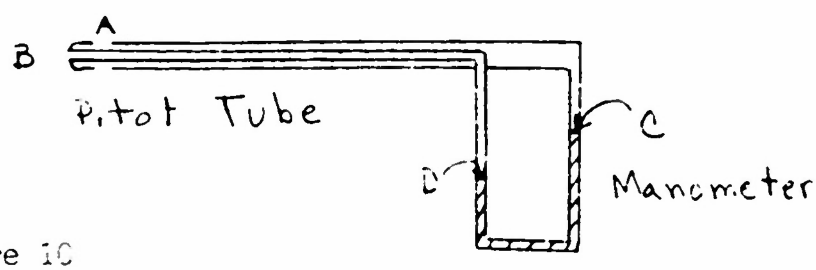

Figure 10

Suppose one wishes now to measure the D.C. air flow in a medium in which an intense sound field exists. First of all the average pressure at the opening A will have two components - (1) the pressure which the medium would have in the absence of the sound field and (2) the acoustic radiation pressure at A. The pressure at C will not in general equal the pressure at A. This is so since the interior system from A to C has its own acoustic properties and it is being driven at A by the variable sound pressure at A. Suppose, for example, that the tube from A to C is uniform in sectional area and is a quarter wavelength long at the frequency of the sound field. AC will then resonate with a pressure antinode at C and consequently the radiation pressure at C will be greater than that at A. Moreover changing the length AC will change this pressure difference. As a concrete example of how this kind of phenomenon can occur, during one phase of experimentation with the siren a small tube, for static pressure measurement, was inserted through the wall of the 10" measuring tube and connected to one end of a U-tube the other end of the U-tube being open to the outside atmosphere. The length of air tubing was about 5 or 10 feet. With the Merlin engines operating at constant speed the siren frequency was varied. The level of liquid in the U-tube varied over a very wide range, the liquid finally blowing out the open end. This effect was, as indicated, due largely to the tuning of the connecting tubing.

Precisely the same kind of effects apply to the opening B and the tubing BC. Moreover, it can be expected that the radiation pressure

at B will be different from that at A. It would appear then that a proper pitot tube for use in intense sound field requires careful acoustic design.

The following items should be considered:

(1) The connecting tubing if it is to be long should be sufficiently narrow so as to properly damp out any waves traveling its length.

(2) The system from A to C (and B to D) should have no large changes in cross sectional area which can introduce extraneous resonances.

(3) The system from A to C should match as nearly as possible that from B to D so as to balance out acoustical effects.

(4) Proper account should be taken of the difference in radiation pressure at A and B. This in general requires a knowledge of the acoustic fields at A and B.

4.12 Acoustic Termination

The loss of the sound absorbing material from the siren pipe termination appears to be due mainly to the large amplitude of the alternating particle velocity rather than to effects of the steady air flow. The use of cheese-cloth interspersed between the layers of unbonded fiberglas and the use of a hardware cloth cover reduced the breaking up and loss of the fibers without any readily apparent effects on the acoustical properties of the termination.

4.13 Personnel Protection

Experience with operations in the intense sound fields arising from radiation from the termination of the tube has indicated the need for acoustic isolation for operating personnel and for the instruments.

Operating personnel work in an area which is near the siren (about 85 feet from the pipe termination) where the sound level is below the pain threshhold for the ear. Due to the complex wave form, the low frequency, and the intensity (sound levels are of the order of 110 db there) masking of speech is virtually complete. Also, hearing damage for long exposures is believed to be likely. Not only does the masking effect deter communication between personnel, but the sound causes an apparently psychological disturbance of the individual which tends to cause difficulty with mental processes. Ear defenders are used by all personnel, of course.

Airborne sound waves and vibration, for example, of a table top, cause spurious operation of electronic equipment due to microphonic tubes.

Accordingly, a sound insulating structure of simple design has been erected for the purpose of providing shelter for personnel and equipment. Although not completed in time for the experiments reported here, this structure will be used in future tests.